Infrared Systems for Tactical Aviation:

An Evolution in Military Affairs?

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Preface

The concept of using natural evolution to understand for how modern organizations adapt to a chaotic, rapidly changing world situation is currently popular in the business world. This study examines whether the chaotic evolutionary development model is pertinent to the U.S. military's ability to adapt to prevailing national security conditions in the twenty-first century. In particular, it examines the evolutionary development of infrared (IR) systems for tactical aviation to understand how the natural evolution model can be applied to the development of military systems, and how that compares with the more traditional development of radar systems. The central argument in this study is that the chaotic evolution of IR systems has successfully influenced the current state of air operations, and further that the natural evolutionary development model offers many useful analogies for how IR systems were developed and employed. Understanding this analogy and its limits may help to create more flexible development systems that can better able to adapt to uncertain security conditions. Finally, this study examines how evolutionary development might be applied to the Revolution in Military Affairs.

I would like to acknowledge my advisors in the Center for Strategy and Technology, Dr. Grant Hammond and Colonel (ret.) Ted Hailes for giving me the time and opportunity to think about this problem. I would also like to thank Lieutenant Colonel Beth Kaspar and Lieutenant Colonel John Brunderman for their intellectual support and encouragement. That being said, the author alone is responsible for the contents of this study.

I. Introduction

Evolutionary development is based on using continuous experimentation and adaptation in changing circumstances to reward success, while allowing, but eventually eliminating, failure. Since this approach is agile, flexible, quick reacting, and thrives on change, it contrasts with strategic planning in which systems are developed in a planned and orderly fashion to meet future requirements. A planned system is rigid, slow to react, and resists or ignores change, which contrasts with how the military traditionally develops weapon systems.

One word that distinguishes between evolutionary and planned development is "chaos." Chaos, like risk, is unavoidable, and hence should be managed rather than avoided. Indeed, a certain degree of chaos is desirable because it generates the necessary set of adaptations and ideas that can eventually be "selected" for evolutionary improvement. The Darwinian concept of "survival of the fittest" can be applied to ideas, systems, and organizations that seek to maintain a competitive advantage.[1]

A simple example that illustrates this line of thinking is IBM's failure to anticipate the switch from mainframe computers and remote terminals to smaller, stand-alone, personal computers, which often is cited as an example of poor strategic planning. In terms of an evolutionary paradigm, the argument is that it was so *impossible* for IBM to logically deduce such a radical development that no strategic plan could have succeeded. Instead of focusing on poor planning, an important conclusion for IBM is to develop an organization that is sufficiently chaotic to develop all relevant fields, while adapting quickly when the "fittest" systems survive. Since chaos is not usually associated with IBM's culture in the 1980's, its failure is not surprising from an evolutionary standpoint. If we substitute the Department of Defense (DoD) for IBM and the fall of the Berlin Wall for the computer revolution, a similar story emerges for national security. The argument is that the radical shift to an information-based society might provide a better guide for military modernization.

The two terms critical to this paper are "chaotic" and "evolutionary." Chaotic does not imply total unpredictability or "a state of utter confusion," but should be thought of in terms of the new science of chaos theory in which order and stability can be derived from inherently unpredictable states. For the purposes of this study, it is useful to think of chaotic as "unplanned" or "other than planned." At the same time,

evolutionary development does not necessarily imply a "process of gradual and relatively peaceful advance," but is the adaptation of systems to a changing environment by an unbiased selection process that rewards success. It can lead to radical, as well as gradual, shifts in a system.

To understand the potential of chaotic evolutionary development, this study considers the historical example of military systems whose development exhibited chaotic evolutionary traits, specifically the development of infrared systems for tactical aviation, which provides a useful example for several reasons. First, the development of IR systems proceeded in a relatively unplanned manner and exhibited many chaotic and evolutionary aspects. Second, IR systems are relevant to current U.S. Air Force (USAF) operations. Third, IR systems can be examined in terms of combat, which is the ultimate test of military systems. Fourth, and perhaps most importantly, the evolutionary development of IR systems can be compared with the more traditional development of radar systems, which also exploit the electromagnetic spectrum for many of the same military tasks.

This study examines three cases of chaotic IR systems development through their development, procurement, and employment across the spectrum of tactical aviation -- air-to-air, air-to-ground, and surface-to-air. The operational implications of IR systems for tactical aviation will also be addressed. The lessons learned from examining these cases and their operational implications offer important insights for current air operations and future development efforts. A later section of this study discusses how the concept of chaotic evolutionary development might apply to the information-based Revolution in Military Affairs (RMA). With this approach, the reader can understand how current IR and radar systems as well as sensor technology systems might be developed in the future.

II. Electromagnetic Spectrum and Military Applications

Until WWII, humans fought under visual conditions because the only portion of the electromagnetic spectrum in which humans could "see" was the extremely small part to which the human eyeball is sensitive. While optical devices (binoculars, optical sights, etc…) greatly improved human vision, fighting was governed by limitations associated with the human eyeball. As a result, soldiers and airmen fought at relatively close range; rarely fought at night; were severely limited by smoke, other obscurants, and weather; and were easily deceived by camouflage and concealment.

Radar

However, the advent of radar greatly expanded the military's ability to "see" and fight, and dramatically affected air operations. In 1940, primitive radar systems had a decisive effect on the Battle of Britain because it extended the Royal Air Force's (RAF) ability to "see" across the English Channel.[2] Given the necessities of war, radar made great strides in development as systems became sufficiently small and rugged to fit on large aircraft, which allowed RAF bombers to "image" the ground for "accurate" night bombing (or at least as accurate as contemporary American daylight bombers).[3] By the end of the war, the Germans had developed radar systems for use on fighter aircraft that limited the nighttime sanctuary for bombers.[4]

Since America entered the war later, it lagged behind in radar development. A year after the Battle of Britain, a developmental US radar system "saw" the Japanese attack on Pearl Harbor while the aircraft were still well out to sea, but this information was not acted upon because the radar was still in developmental testing.[5] However, the United States eventually embraced the new technology, as American bombers used radar to "see" through the smoke and haze of the Ruhr industrial area and the usually cloudy European weather. The United States also developed radar-equipped night fighters for use in the Pacific theater (P-61 Black

Widows).[6] This technology also helped turn the tide against the U-boats in the Battle of the Atlantic.[7] Tactical aviation was not the only wartime beneficiary of radar. Admiral Nimitz in the Pacific Theater of WWII considered radar to be as revolutionary as the steam engine.[8]

The wartime success of radar ensured that this technology would be heavily exploited after the war. Military requirements for making radar units lighter with better resolution and lower power consumption, and for specific purposes such as weather detection continued to increase. The story of radar-based systems since WWII has been characterized by technology pull, which signifies that military requirements spur the development of technology. However, despite the tremendous advantages offered by this new technology for military operations, radar had some serious liabilities and limitations in comparison with human vision. These included low resolution, large size and power requirements, and radar's non-intuitive nature. The most glaring difference was the "active" nature of radar systems and their subsequent susceptibility to countermeasures. It is for this reason that the technological community turned to the development of other capabilities, of which infrared technologies are a critical example.

Infrared Spectrum

The infrared portion of the electromagnetic spectrum offers many of the benefits associated with radar but without its limitations. Since the infrared spectrum is just outside the visible spectrum, the concept for design and the imagery produced by infrared systems is relatively straightforward. The systems simulate human vision to produce imagery that "looks" like a visual picture.

The difference between radar and infrared systems at the end of WWII was that radar was making substantial contributions to the war effort, while the benefits of infrared systems were still largely theoretical. The only wartime infrared system in the Allied inventory in WWII was a sniper scope, which was employed at Iwo Jima and allowed nighttime targeting at a range of 75 yards.[9] The Germans used IR searchlights and simple IR vision devices to conduct armor attacks at night, but these experiments were largely unsuccessful.[10] Therefore, while radar provided "pulled" military R&D, IR systems largely relied on technology push,

which largely explains differences in the patterns of developing radar and IR systems.

Throughout the Cold War, radar systems dominated tactical aviation applications. The prospect of war with the Soviet Union decisively influenced the development of radar systems and technologies. Operationally, the United States emphasized the development of fighter aircraft that could destroy Soviet bombers at long range with radar missiles, and low flying attack aircraft that used terrain-following radar to avoid the radars of the Soviet integrated air defense system (IADS). However, there were many opportunities for the DoD to pursue chaotic evolutionary development in three areas of tactical aviation: air-to-air, air-to-ground, and surface-to-air. As a result, IR systems made inroads as both as a compliment to and competitor with radar systems.

Military Applications

Air-to-Air: Sidewinder. In the 1960's, the F-4 Phantom was the USAF's primary fighter and was armed with the AIM-7 Sparrow radar-guided missile. The Sparrow had been under development for more than a decade, and was a large, expensive, long-range, all-weather missile that gave the Phantom a marked advantage in the air-to-air combat against Soviet bombers.[11] Not surprisingly, when the USAF found itself fighting the Vietnam War, the enemy did not fly in bad weather. At the same time, restrictive rules of engagement, which were established after the third Sparrow destroyed an American aircraft, negated its range advantage.[12] After that friendly fire incident, the pilots had to establish positive identification visually before firing, and once inside visual range, the enemy's small, maneuverable fighters had the advantage. Since the Phantom fighter did not have an internal gun, it relied on the Sparrow's radar guidance, which was poorly suited to close-in, visual aerial combat. The Sparrow did not have its own radar transmitter, but instead relied on the aircraft's radar to guide it to the target. Known as semi-active radar homing, this requires the attacking aircraft to keep its nose (radome) pointed in the direction of the opposing fighter.[13] Given the high closing speeds of modern fighter aircraft, enemy fighters often could fire their own short-range weapons while the Sparrow was in flight.

In evolutionary terms, the USAF had an unfilled niche that was filled by the IR-guided Sidewinder missile. Rather than being a product of

the standard military research and development process, a small team at the Naval Weapons Center at China Lake pursued a textbook case of chaotic evolutionary development to create the prototype for the Sidewinder, which it did without official support and in opposition to official guidance.[14] The team at China Lake developed an infrared-guided "fire-and-forget" missile, in which the pilot used the missile's IR seeker to "lock on" to the target. When fired, the missile would guide on the infrared emissions of the target aircraft's jet engines, which required no further action from the pilot who could look for another target or evade enemy counter-action.

Even after the Navy adopted the Sidewinder in the mid-1950's, the USAF ignored the IR missile because Air Force requirements clearly specified an "all weather capability," which the Sidewinder did not possess.[15] However, the Sidewinder was eventually adopted by USAF and proved to be extremely effective. For example, in Operation Rolling Thunder (1965-68), Sparrow missiles accounted for twenty-seven air-to-air kills, while the Sidewinder accounted for twenty-nine kills. In Operation Linebacker (1971-73), Sparrows accounted for twenty-nine air-to-air kills while the Sidewinder accounted for fifty-two kills.[16] Thus, the Sidewinder missile consistently had twice the kill ratio of aircraft kills per missile launched in comparison with the Sparrow missile during the Vietnam War.[17] Furthermore, the Sidewinder was considerably cheaper than the Sparrow, and it is estimated that its development costs were one-tenth that of the Sparrow missile.[18]

Air-to-Air: AMRAAM and AIM-9L. The AMRAAM (Advanced Medium Range Air-Air Missile) was developed in a traditional program to replace the Sparrow missile, but the program was plagued by delays and cost overruns.[19] However, the AMRAAM is a success story whose relatively small "fire-and-forget" radar missile is guided toward enemy aircraft in three stages. While on the aircraft, the missile receives target information from the aircraft's radar system, which predicts where the enemy aircraft is going and then fires the AMRAAM toward that spot. Then, the AMRAAM flies to that spot using internal inertial guidance systems, and when it reaches the target area the AMRAAM uses its internal radar to get a final fix on the target for terminal guidance.[20] While the missile has a long range, it uses its internal radar for a short time, which means that the radar can be small, low power, and vulnerable to jamming for only a short time. By merging the two different sensing mechanisms of inertial navigation and radar, AMRAAM designers

overcame many of the limitations associated with radar guided missiles. By this standard, AMRAAM represents a revolutionary advancement in air-to-air weapons.

The Sidewinder, given its success in the Vietnam War, also became part of the traditional USAF acquisition system, but continued on an evolutionary development path. Several generations of Sidewinder missiles took advantage of more reliable and sensitive IR detectors until the AIM-9L seeker, which was so sensitive that it could "see" the heat produced by skin friction on the front of the aircraft and the plume trailing behind. No longer must a pilot maneuver to the rear of an enemy aircraft to point Sidewinder missiles at the hot engine exhaust. As an "all aspect" missile, like the radar guided Sparrow and AMRAAM, the all-aspect Sidewinder was an extraordinarily lethal weapon. During the Falklands conflict, the AIM-9L transformed the air-to-ground British Harriers into potent fleet defense interceptors, as seen by the destruction of eighteen Argentine planes with only twenty-six missiles for a seventy-five percent success rate.[21]

Air-to-Ground: Low Altitude Navigation and Targeting Infrared for Night (LANTIRN). In view of the success of smart bombs in the later stages of the Vietnam War, the USAF began to develop a wide range of "smarter" munitions. The Maverick Imaging Infrared missile, which was a natural upgrade from the TV-guided Maverick, was able to "see" at night and through smoke. The problem with Maverick missiles was that they required significant attention from the weapons officer who had to select and lock-on to targets. As the USAF moved away from the F-4 fighter and filled its inventory with single seat A-10 and F-16 aircraft, the weapons officer became a rare breed. Therefore, the story of the Maverick IR missile is really the story of the system that was supposed to make it usable in combat for the post-Vietnam USAF, which became LANTIRN.

The LANTIRN system consisted of two pods that could be retrofitted onto existing aircraft for a night attack capability against armor, which was critical to defending against a Warsaw Pact attack through the Fulda Gap in West Germany. LANTIRN was designed to enable F-16 and A-10 pilots to search for and engage tanks at night. While one pod provided a laser range finder and Maverick missile targeting system, the other pod provided night navigation capability, which consisted of an infrared picture displayed on a wide-angle head-up display that the pilot viewed through the display to "see" the outside world. In the mid-80's, the first LANTIRN flight simulator for the F-16 developed at the Air

Force Human Resources Lab at Williams AFB, Arizona, was a state-of-the-art simulator with a fully functional cockpit that used radar imagery and simulated LANTIRN infrared imagery.[22]

When F-16 pilots used the simulator, they were less enthusiastic than the development team. They informed the developers that flying from the IR image was like "looking through a soda straw," while being color-blind and lacking depth perception. However, they were supposed to use this system while flying at high speed near the ground while navigating, avoiding the terrain, scanning for threats, and engaging targets. LANTIRN was a technological marvel but was limited by a flawed operational concept.[23]

Although LANTIRN was an initial failure, it eventually became successful when it was adapted for the conversion of the F-15 fighter aircraft in the late 1980's. When the F-15 was being designed in the 1970's, it was designed to be a "pure" air superiority fighter. However, a later model of the F-15, the F-15E Strike Eagle, is the USAF's premier attack aircraft. The keys to its "revolutionary" change in mission were adding a second seat, refining its radar, and adding LANTIRN pods, which would allow two aviators to navigate, avoid terrain, scan for threats, and engage targets. This "chaotic" merger of the F-15 airframe and LANTIRN pods created a significant operational success in the 1990's.

Surface-to-Air: Stinger. In December 1979, when the Soviet Union staged a military coup d'etat in Afghanistan, it began a nine-year conflict between the Soviet military and the Muslim freedom fighters, known as Mujahideen. The Soviet military and its advanced technology fought primarily against small bands of poorly armed guerrilla fighters. Nevertheless, reminiscent in many ways of America's Vietnam experience, the Soviets suffered a severe strategic defeat.[24] Much of the credit for the Soviets' defeat goes to the introduction of the Stinger missile into that conflict.

The Stinger is a small IR missile that was developed and procured for the U.S. Army to give infantrymen a portable air defense capability, which is a surface-to-air missile equivalent of the Sidewinder. It was so effective that the Central Intelligence Agency initially advised against supplying Stingers to the Mujahideen.[25] However, after CIA-supplied Soviet Strella and British Blowpipe missiles failed to significantly curb the use of Soviet airpower, America supplied Stingers to the guerrillas, which immediately affected the conflict.[26] Soviet losses of aircraft, especially helicopters, rose sharply, and eventually reached 2,000. Soviet fighter

aircraft were forced to conduct high-altitude operations, which severely limited their effectiveness. When the Soviets were forced to severely restrict all air operations, it severely affected their military capabilities.[27] Thus, the relatively cheap and simple Stinger, when used in its "chaotic" role as a guerrilla weapon, had significant consequences for U.S. military capabilities.

The Stinger's unplanned success is only part of its chaotic story because its second- and third-order chaotic effects continue to haunt the United States. For example, the Taliban, successors to the Mujahideen of Afghanistan, are in power partly because of American intervention, and now shelter Usama-bin-Laden, America's most wanted terrorist.[28] China has increased its military capability by copying Stinger technology supplied by Pakistan, which helped to ship Stingers to the Mujahideen. As partial repayment, Pakistan got advanced missile and nuclear technology from China and, in turn, proliferated that technology to North Korea to update the SCUD missiles that threaten American troops. The unintended consequence of supplying Stinger missiles to the Afghan rebels is a perfect example of the effects associated with chaos theory.[29]

Surface-to-Air: Yom Kippur War. In the 1973 Yom Kippur War, surface-to-air engagements were critical to the outcome of the air war. None of the Arab surface-to-air missile systems were particularly effective. Roughly 2,000-3,000 radar-guided missiles were launched but destroyed only forty Israeli aircraft.[30] Additionally they launched more than 5,000 SA-7 Strella's which destroyed only thirty aircraft.[31] However, these SAMs were effective because the Israeli's were forced to shift their ground attack missions from the planned role of supporting the army to counter-SAM missions.[32] While they eventually destroyed many SAM missiles, the chaotic diversion of effort nearly cost Israel the war.[33]

While the Israeli forces had dealt successfully with Egyptian radar missiles in previous skirmishes over the Suez Canal in previous years, in the Yom Kippur War a Western air force faced a "massive, integrated SAM and anti-aircraft gun air defense network" for the first time.[34] The tactics and training that had worked for Israel in the past were no longer effective against this new threat, particularly, the tactic of using low-level flights to avoid or break radar contact.[35] Given the need to press their ground attacks early while the Israeli Army mobilized, there was no time for the Israeli Air Force (IAF) to adapt. However, a rapid resupply effort by the Americans, including some of the latest electronic countermeasures, helped the IAF recover.[36] Nevertheless, only the

disruption of the air defense network by the advance of the ground forces later in the war, finally allowed the IAF to operate the way it had intended.[37]

Post-Cold War Implications

At the beginning of the 1990's, national security underwent fundamental changes as the United States faced the "post Cold War" world. The USAF soon faced the challenges of a more chaotic world, which affected tactical aviation on several levels.

Air-to-Air. There was little reason to doubt USAF capabilities in the air-to-air arena. The USAF still used the Sparrow, but the AMRAAM promised to be far more effective, and there was an upgraded and demonstrably more lethal Sidewinder.[38] In addition, the Israeli Air Force had demonstrated the superiority of Western pilots and aircraft against Soviet proxies in numerous conflicts. In the aerial battles of the 1970's and 1980's, the United States developed air-to-air missile systems (and Israeli variants) that turned Israeli air superiority into air dominance.[39] With similar training, aircraft, and even better missile systems, there was no reason to doubt that the USAF would dominate air-to-air combat.

The 1973 Yom Kippur War saw more air-to-air combat than in any previous Arab-Israeli war, which Israel had dominated because of its superior pilots and missiles.[40] Israel downed 277 Arab aircraft while only losing six in aerial combat. Roughly sixty-five percent of these kills were attributable to IR-guided missiles (Sidewinders and Israeli variants), while Sparrow missiles accounted for only five percent.[41] In the 1982 Lebanon conflict, the Israeli Air Force (IAF) used both IR and radar missiles even more effectively against the Syrian Air Force. In that conflict, Sparrow missiles were not particularly effective but served the tactical purpose of breaking up Syrian formations. The all-aspect Sidewinder gave a major qualitative advantage to the IAF and accounted for most of the kills.[42]

As the operational concept grew to include airborne warning and control platforms such as variants of the US Navy's Hawkeye, balance in the air shifted from being merely one-sided to that of total dominance. This was demonstrated by the IAF's eighty-five to zero aerial victory margin over Syria.[43] Eventually, the Syrian Air Force believed that missions against the IAF were suicidal, and some Syrian pilots ejected at

the first signal from radar warning receivers.[44] The air-to-air "turkey shoot" was spectacular and confirmed Israeli mastery in air-to-air combat that had been demonstrated in previous wars.

The IAF used the Sidewinder with great success, and used their wartime experience to modify the missile. When Israel first used the Sidewinder missile, the primary enemy aircraft often encountered was the MiG-23 Flogger, which even by Soviet standards is a robust, sturdy airplane. Israel learned that the Sidewinders were so accurate that they often flew into the tailpipes of the Flogger jet engines, which destroyed the engine but contained the blast of the Sidewinder's small warhead. The pilot often bailed out of the Flogger to return and fight another day. Since the pilot is an integral part of the fighter system, and skilled pilots were at a premium, allowing the most critical part of the fighter system escape from air-to-air engagements was ineffective. Therefore, Israel put a larger warhead in the Sidewinder missile and renamed it the Python, and when the Python hit a MiG-23, it destroyed the entire aircraft.[45]

Air-to-Ground. Most air-to-ground development efforts during the Cold War focused on attack aircraft that were designed to penetrate Soviet radar systems. The B-1 bomber was designed to go under radar coverage, while the F-117 stealth fighter was designed to be "invisible" to enemy radar.[46] However, there were reasons to doubt the value of this high technology approach. For example, the B-1 bomber was known as a "hanger queen" because of its serious maintenance problems and insufficient electronic countermeasures.[47] Furthermore, the F-117 bombing of an unoccupied field during Operation Just Cause in Panama in 1989 was a less than auspicious combat debut.[48] By the early 1990's, there were serious doubts about USAF investments in the high-technology attack aircraft that were primarily designed to penetrate the now-defunct Soviet air defenses.[49]

Surface-to-Air. The ability of the USAF to operate in a surface-to-air threat environment was viewed with cautious optimism. In the Bekka Valley in 1982, Israel demonstrated that a radar-based integrated air defense system, which had generated so many problems during the Yom Kippur War, could be defeated. Furthermore, older generation IR missiles did not pose a significant threat because decoys could fool these missiles.[50] But the single experience in the Bekka Valley could not easily be extrapolated to all of the situations that the USAF might confront. The entire engagement over the Bekka Valley was over so quickly and apparently effortlessly that it was more of a lesson in Israeli military skills

and Syrian incompetence than a true test of air defenses.[51] In addition, Israel was intimately familiar with the combat area and their opponent, and had practiced against Syrian air defenses for nearly a year in the Negev desert.[52] Such a situation was highly unlikely for U.S. forces facing a chaotic world where threats might arise anywhere and anytime. To further complicate matters, the Afghanistan conflict had demonstrated that modern IR missiles could be extremely effective even when used in small numbers in a primitive air defense system. Although the USAF had developed platforms that could survive the SAM threat, the issue remained in doubt as America headed into its first post-Cold War conflict.

Surface to Air: Near Defeat Spurs Adaptation and Evolution. The requirement for close air support prevented the IAF from experimenting and adapting during the Yom Kippur War. During the next major conflict between the IAF and Arab SAMs over the Bekka Valley in Lebanon in 1982, Syrian forces employed nearly the same mixture of air defense assets that had been so successful in 1973, notably radar-guided SA-2, SA-3, and SA-6 long-range missiles integrated with SA-7 infrared missiles, and numerous types of anti-aircraft (AA) guns. However, the IAF was prepared this time.[53] The Israeli's nullified the heat-seeking Strellas with flares and thermal balloons, and lost only one aircraft to SA-7s despite many low level attacks.[54] Their ability to dominate radar-guided missiles was even more spectacular -- the IAF destroyed seventeen of nineteen Syrian SA-6 sites and several SA-2 and SA-3 sites in less than twenty minutes of active combat.[55]

Although Israel has used security and deliberate misinformation to protect its radar SAM-defeating secrets, the basis of its success is well known. The Israeli's had superior pre-attack intelligence on the location and emission characteristics of the Syrian SAMs. They began the attack with remotely piloted vehicles, some with sensors to pinpoint the missile sites, some as decoys to entice the radars to emit, and some with lethal warheads to home-in on radar emissions. Once the sites were located, a well-coordinated attack plan was executed with the help of Hawkeye airborne warning and control aircraft. The attack aircraft were well protected with the latest countermeasures, including support from large dedicated (Boeing 707 variant) electronic countermeasures aircraft. Even some surface-to-surface missiles and artillery shells were specially designed to attack air defense radars.[56] No Israeli aircraft were lost, and from the start of the conflict, the Syrian air defense system was effectively destroyed.

III. Operational Implications of Infrared Systems

As America prepared to fight Iraq in the Persian Gulf War, many commentators looked for lessons learned that might apply to the upcoming war. In hindsight, it is quite clear that the Israeli experiences of using Western aircraft, pilots, and missiles provided significant tests for the combat methods and results that prevailed during the Gulf War. In the air campaigns over Serbia and Kosovo in the late 1990's, the relationship between radar and IR systems and air operations has fundamentally changed how the USAF operates.

Air-to-Air

In neither Desert Storm nor Allied Force did enemy air forces, despite being equipped with fairly modern fighters, seriously challenge coalition air forces. Iraq attempted several interceptor sorties during the opening days of Desert Storm, but reached the same conclusion as had the Syrians over the Bekka Valley that flying against Western air forces would be suicidal. Coalition forces shot down 41 Iraqi aircraft, 24 with Sparrows and 12 with Sidewinders.[57] An Iraqi MiG-25 may have scored a single aerial kill just before it was shot down.[58] In a sign of how completely the coalition forces dominated the aerial battles, Iraqi aircraft were not safe even *after* they retreated into hardened shelters, because coalition aircraft systematically destroyed the shelters and anything inside those shelters.[59] The Iraqi's were forced into the truly desperate act of running the gauntlet of coalition combat air patrols in order to escape to Iran, a country with which they were still technically at war.[60]

Over Kosovo and Serbia, the story was much the same. While the enemy air forces had capable aircraft, such as the MiG-29, NATO forces were vastly superior. The same combination of superior aircraft, pilots, missile systems, and situational awareness that had served the Israeli Air Force produced one-sided aerial battles. As with the Israeli experience, the principal lessons from the air-to-air contests of the 1990's was that the West is totally dominant.

Air-to-Ground

Operation Desert Storm – The IR War. Historians have claimed many "firsts" for the Persian Gulf War: the first Info War, the first RMA war, and the first successful air war. In any case, Desert Storm was the first war in which IR systems played a dominant role. The nightly news video that showed the effectiveness of precision-guided weaponry nearly always involved IR systems. And F-15E Strike Eagles equipped with LANTIRN pods were very effective, which led to rushing more LANTIRN systems into the theater.[61]

The "chaotic" use of IR systems increased throughout the war. The small, low resolution image from Maverick missile seekers, which were designed with sufficient resolution to verify a target, were used instead by A-10 pilots as "mini-LANTIRNs" to search for targets in the desert.[62] F-111 pilots used their Vietnam War vintage Pave Tack pods to attack tanks because tank armor stayed warm, and therefore highly visible to even low-resolution IR systems, long after the desert sand cooled.[63] The F-117 stealth fighter, the most modern strike aircraft of the war, had no radar at all. Following the dictum that a stealthy aircraft should not emit, the F-117 relied on IR systems for navigation and targeting.[64] During Desert Storm, IR systems demonstrated that these had evolved to the point of being critical to the USAF domination of the battlefield.[65]

Kosovo -- The GPS War. Away from the desert, the weather limitations associated with IR systems were even more critical. An important system during the Kosovo conflict was the B-2 bomber and the Joint Direct Attack Munition (JDAM), which is guided by an inertial navigation system that uses the Global Positioning System (GPS). GPS was unaffected by weather, which meant that the B-2 was one of the few systems that could bomb through the overcast weather which characterized the first few weeks of the air campaign.[66]

The initial development of a satellite-based navigation system was as complex as that for the Sidewinder missile.[67] While the B-2 bomber was designed to drop nuclear bombs on mobile Soviet ballistic missile launchers during a nuclear war, the B-2 bomber was highly effective against stationary targets, such as bridges and airfields, during a small-scale conflict. Although not part of the development of IR systems, the systems used to bomb Serbia provide further evidence of "chaotic" evolutionary development.

Kosovo – Evolution of Tomcat Fighter. The U.S. Navy's F-14 Tomcat aircraft underwent a radical change between Desert Storm and Allied Force. The Tomcat symbolizes the radar-based fighter aircraft. It uses a large radar to support the AIM-54 Phoenix missile. The Phoenix grew from the same radar-focused planning, as did the Sparrow missile.[68] Its large radar, coupled with its highly capable fire control system, gives the F-14 an extremely long range.[69] Designed to knock down Soviet bombers and cruise missiles at long range, the F-14 was on its way to extinction when the Cold War ended. In its time and role in fleet defense, the Tomcat was highly capable, but during the Gulf War, the rules of engagement did not allow the extremely long-range missile engagements in which the combination of Phoenix missiles and Tomcat aircraft specialized.[70] The problem was that the Tomcat was a superb aircraft that lacked a role in the post Cold War world.

However, the Tomcat survived because U.S. Navy lacked a precision guided capability during Desert Storm. By merging the Tomcat and its heavy weapons load with LANTIRN pods, the Navy was able to create "Strikecats" relatively quickly and inexpensively.[71] Virtually without precision capability in the early 1990s, U.S. Navy aircraft effectively participated in Operation Allied Force using almost exclusively precision weapons.

Surface-to-Air

Air Dominance. It is difficult to compare the Gulf War and the Kosovo conflict with the USAF's previous experiences in the Vietnam War. Quantitative numbers or percentages of kills are not relevant because of the disparate nature of these air wars.[72] A more relevant comparison would be qualitative. Radar missiles posed a constant danger over North Vietnam, and IR missiles were a threat to low flying, slow aircraft, especially helicopters, in South Vietnam. However, in the Persian Gulf War the Iraqi air defense system was effectively destroyed in the opening minutes of conflict. This was accomplished through the use of superior intelligence, radar-baiting decoys, electronic countermeasures, well-coordinated command and control, anti-radiation missiles, and conventional attacks with special operations forces and Apache helicopters. The simultaneous attack against the entire air defense system

produced quick, overwhelming victory.[73] After the first few days of suppressing Iraqi air defenses, there was virtually no radar missile threat.[74]

However, the infrared missile threat during the Persian Gulf War was much *greater* than during the Vietnam or Israeli conflicts and it persisted throughout the war because the Allied air forces did not have a way to suppress or destroy passive IR systems. The Allied forces, like the Soviets in Afghanistan, chose the tactic of remaining at medium-to-high altitudes to avoid the IR threat.[75] In the decade since the Persian Gulf War, Allied aircraft enforcing no-fly zones continue to attack radar missile sites with virtual impunity while staying above the IR missile threat. In Kosovo, the trend of a lower air defense threat continued. The truly amazing statistic of no Allied aircrew and only two aircraft lost to enemy air defenses during a seventy-nine day air campaign speaks for itself. However, once again Allied aircrews were forced to conduct operations at altitudes above the IR threat, which in practical terms meant that medium altitude attacks against tactical targets in Kosovo were routinely criticized for their ineffectiveness.[76] As in the Afghanistan conflict, relatively simple and cheap IR missiles seriously eroded the effectiveness of a modern air force.

Apache Helicopters. The Apache fiasco, known as Task Force Hawk, represents the most glaring example of doctrinal mismatch during Operation Allied Force. Since low, slow-flying aircraft cannot survive in the face of low altitude, IR missiles, the Army believed that the only way to suppress passive IR systems during Apache operations was to blanket the area with shrapnel in order to kill or damage any "soft" targets. To accomplish this, the Army deployed the Multiple Launch Rocket System with Task Force Hawk because after a devastating rocket artillery strike, the Apaches would be able to safely fly in and destroy remaining hard targets.[77] While this approach is consistent with doctrine, blanketing a large area with shrapnel is impractical during humanitarian operations, such as Kosovo. Further, this defied the conventional wisdom that the Army must make its helicopter deployment lighter and leaner so that it can incorporate Apache strike forces into air campaigns. Thus, the decision to bring Apache helicopters into an air campaign that would operate in the presence of unsuppressed low-level IR threats missed many of the lessons learned during recent conflicts.

IV. Current Technologies and Tactical Aviation

Air-to-Air

The most telling statistic about USAF air-to-air dominance is that a Western piloted F-15 or F-16 aircraft has *never* been shot down in air-to-air combat.[78] Much of the credit belongs with the development of superior air-to-air missiles guided by radar and IR sensors. The AMRAAM, first used in the Persian Gulf War, remains a state-of-the-art radar-guided missile. Despite minor improvements in lethality, range, and electronic counter-countermeasures, it is not clear that a "better" radar-guided missile is necessary, as shown by the continued success of the AMRAAM in war. The all-aspect Sidewinder has been equally successful. The program to replace the Sidewinder with an ASRAAM (Advanced *Short*-Range Air-Air Missile) or AIM-9X has not produced any significant improvements.[79] Nonetheless, the ASRAAM missile will go through one more evolutionary improvement, which will be based on the threat posed by the MiG-29 aircraft and its AA-11 Archer missile.[80]

As the Soviet Union fell behind the West in the fields of electronics and computational power, their ability to field advanced radar systems declined. As a result, the Soviets increasingly relied on more reliable, easier to design, computationally simpler, and tougher-to-jam IR systems, which surprised Western intelligence agencies. For example, when the MiG-29 Fulcrum aircraft was fielded in the 1980s, its radar system and associated missile were impressive by Soviet standards but at least a generation behind Western systems. However, it also had a bump on the nose, which was not an electronic warfare antenna as first suspected, but an Infrared Search and Track System (IRST), which was the first to be fielded in an operational fighter.[81] Once merged with a laser range finder, the IR system could detect aircraft *and* provide targeting data at longer ranges without alerting the target aircraft that it had been detected. Even if a target aircraft suspected it was being tracked, there is no practical way to "jam" this IR system. The MiG-29's IR system was integrated with the improved IR missile, known as the AA-11 Archer, which not only had the all-aspect feature of the latest Sidewinders, but it also had "off-boresight" capability – meaning that the missile could "look"

to its left and right to "see" target aircraft. Thus, the pilot could fire a missile without pointing the aircraft nose at the target aircraft, as Sidewinder equipped pilots must do. This expands the firing envelope for the missile, saves precious seconds in a dogfight, and compliments the maneuverability of a fighter because it is much easier to maneuver the fighter into a firing position. In addition, Russian pilots had a helmet-mounted thermal sight which permitted them to aim the missile merely by looking at the targeted aircraft, in effect giving them an IR "heads-up display" wherever they looked, not just on the front of the instrument panel, as in Western cockpits. The details of this system did not fully emerge until the East German MiG-29's became part of the unified Germany's Luftwaffe. Once they did, it was clear that an IR-equipped MiG-29, flown by a skilled pilot, had an advantage, and the AA-11 Archer missile seriously challenges the technological primacy of the Sidewinder.[82]

While it is not clear that the Archer represents a shortfall in our air superiority capabilities, the USAF is moving to close the IR missile gap. Until then, the USAF advantage in pilot training, situational awareness systems, and long-range missiles make the prospect of an evenly balanced close-in dogfight highly unlikely.[83] However, the USAF acquisition system has been energized to conduct a significant development program to develop a U.S. equivalent to the Archer.[84]

Despite the development of its highly capable missiles, the USAF has accepted engineering complexity and design tradeoffs to ensure the basic 20mm cannon will still remain integral to future fighter aircraft. This decision is based on Vietnam-era lessons learned in the F-4 community, yet these lessons may not be relevant. The F-4 functioned as a dogfighter because the USAF lacked the situational awareness in the 1960s to handle long-range missile engagements and because of the serious tactical limitations with semi-active radar homing. However, the F-22 aircraft has none of these limitations. It will carry AMRAAM missiles, which are a true "fire-and-forget" long-range radar missile, as well as advanced Sidewinders that will allow short range kills without the traditional need to fly directly toward the enemy aircraft. In addition, the USAF has largely solved the Identification Friend-or-Foe (IFF) problem that hindered missile engagements during the Vietnam War.[85] In the 1960's, the failure to design the F-4 aircraft to dogfight with the MiG-21 in the MiG's operational envelope was a serious oversight. However,

designing the F-22 to dogfight against the MiG-21 in the MiG's operational envelope could be a serious mistake.

Air-to-Ground

Since 1990, IR systems helped the USAF significantly improve the ability to deliver precision weapons and conduct around-the-clock operations. In Allied Force, U.S. forces improved their performance by demonstrating unparalleled all-weather performance and nearly total precision.[86] Today, numerous precision standoff weapons are in advanced development stages and will enter the USAF inventory in the near future further enhancing performance.[87] Systems that can selectively engage multiple targets, such as the Low Cost Autonomous Strike System (LOCASS) and the Sensor-Fuzed Weapon, are only slightly further behind in development.

Three technological developments are making these weapons feasible now. With costs driven lower by the civilian sector, IR sensors and GPS receivers are now sufficiently inexpensive so that these can be put on expendable munitions, not just delivery platforms. Furthermore, the microprocessor revolution has improved the "brains" of munitions, which has important effects for the new generation of "brilliant" munitions. While each technological development is powerful, merging these three technologies is producing a technological breakthrough.

Surface-to-Air

There are differences between the effectiveness of radar and IR missiles in denying U.S. aircraft the use of airspace to prosecute missions. Radar missiles have been unsuccessful against USAF aircraft while IR missiles have been spectacularly *successful*. In the Gulf War, the no-fly zone over Iraqi, and in the air over Kosovo and Serbia, the airspace below 15,000 feet has been virtually off-limits to Allied aircraft given the threat posed by IR missiles. Further, USAF aircraft have a limited ability to reduce their signature against IR missiles and virtually no way to locate or suppress these passive systems. The dangers associated with low altitude operations were demonstrated by the loss of more than one dozen low

flying unmanned aerial vehicles during Operation Allied Force.[88] The USAF has successfully used jamming, stealth aircraft, special operations raids (the Pave Low-led Apache attack on early warning radars in the Gulf War), and information warfare to combat radar missiles.[89] The implication is that the USAF has virtually conquered the radar threat, while the IR threat in the low-level environment remains a problem.[90] Operation Allied Force shows the result of the USAF's pulling technology to develop advanced radar systems and countermeasures in contrast with incorporating and countering IR systems at whatever pace the technology evolves. If then Allied Force is the norm for future air campaigns, this poses serious doctrinal, training, and acquisition issues for the USAF.

For now, the USAF operates its aircraft above 15,000 feet to avoid the IR threat. This raises several difficult choices. If the limit of 15,000 feet becomes a permanent tactic, then the low-level flying and dogfighting skills, which were the hallmarks of Cold War fighter pilots, are irrelevant.[91]

Future aggressors may then notice that shorter-range IR systems were virtually unchallenged by coalition aircraft. If regional powers invest their limited resources in IR systems, the 15,000-foot limit could constrain USAF operations, including UAV sensor platforms. By relying on camouflage, concealment, deception, and humanitarian concerns and placing military materiel in close proximity to sensitive sites, a potential aggressor could potentially shield its forces from USAF long-range weaponry. When combined with the ability to jam or spoof some of the USAF's precision guided weaponry, we might see the development of an uneasy standoff in which USAF aircraft were safe above 15,000 feet but unable to effectively strike enemy forces. The current U.S. military strategy, which relies heavily on airpower, would be undermined.

And if the USAF is unwilling to be banished from low-level operations, it must re-evaluate its approach to IR systems. Since the current trend toward less expensive sensors and smarter microprocessors strongly favors the missile developers, there is no straightforward solution to suppressing or destroying passive systems. Catching up to and staying ahead of the IR missile threat would require a program with the resources and priority of a traditional planned program and the flexibility and adaptability of a chaotic evolutionary program.

The airmen that led Allied Forces believe that future generations of radar missiles and interceptor aircraft will pose a serious challenge to the ability of the USAF to maintain air dominance.[92] Preliminary lessons

learned from Kosovo include the need for larger numbers of more capable jamming aircraft, suppression aircraft, and procurement of the F-22.[93] In addition, the one combat mission that airmen are willing to relegate to "unmanned" aircraft is the suppression and destruction of enemy radar air defenses. As a result of these operational requirements, the USAF will be better able to meet future radar threats.[94]

But what if the radar missile threat does not materialize? Certainly, any regional power may have learned a different lesson than the need to buy advanced long-range air defense systems. Interceptor aircraft and advanced radar SAMs are expensive systems that require significant training and maintenance support. In Operation Allied Force, stealthy aircraft had to plan missions in conjunction with electronic support aircraft, but radar guided missile systems had little effect on the air campaign and many were eventually destroyed.[95]

Future Developments -- Millimeter Wave. The millimeter wave (MMW) portion of the spectrum lies between infrared and radar frequencies/wavelengths (approximately 10 – 100 GHz). The millimeter wave spectrum, as the crossover point between radar and IR systems, represents the last untapped region of the spectrum for sensor developers to exploit for tactical aviation. Fortunately, MMW systems offer great promise because these could combine the benefits of IR systems and radar systems while minimizing their corresponding limitations. While MMW systems can be developed both as IR and as radar systems, some innovative MMW system concepts can combine the elements of imaging (IR) and processed (radar) systems.

Summary

One lesson learned from the development of IR systems is that the evolution in military affairs is in progress, as seen by the way in which the military is exploiting IR systems, but there is no reason to believe that this state of affairs is unique to IR system development. Once the concept of chaotic evolutionary development is understood, many examples of such development in military systems development can be recognized. The next section discusses how these developments compare with the concept of natural evolution.

V. Concept of Natural Evolution

Just as in nature, where natural selection has produced complex and varied life forms for many specialized niches; in military affairs, the forces of combat selection have produced IR systems that perform highly specialized functions in all facets of tactical aviation. The chaotic development and use of IR guided air-to-air missiles, IR targeting systems, and IR SAMs have profoundly influenced all areas of aerial combat. A less obvious, but perhaps more important, similarity is that evolutionary development can produce "revolutionary" improvements in capability.[96] The gradual incorporation of advanced sensor technology into the Sidewinder missile led to increases in capability once the seeker head was sufficiently sensitive to view aircraft from all aspects. This is a classic feature of chaotic systems, in which small changes can have large long-term consequences.[97] It is also similar to events in with nature that lead to "revolutionary" changes.

The development of IR systems has contributed to a radical change in tactical aviation operations because it alters how USAF aircraft fly and fight. USAF aircraft no longer fly at low level to avoid radar, but now operate as high-altitude standoff shooters so that they can avoid IR missiles, which is a radically different method of accomplishing USAF attack missions. LANTIRN has also changed USAF combat operations. While it initially failed in its planned role of enabling aircraft to attack small, high value targets, it eventually succeeded after the USAF developed a two seat attack aircraft, the F-15E Strike Eagle, and the Navy converted the F-14 Tomcat. Further, LANTIRN may now become successful in single seat aircraft because military operations have shifted away from low-level flights, which widens LANTIRN's field of view.

Another similarity with nature is that evolutionary development is often convergent. For example, in the case of missile systems, the radar missile became "fire and forget" with the introduction of AMRAAM, while the IR Sidewinder became all aspect "fire and forget" with the introduction of the "L" model. Radar developers sought shorter wavelengths for greater resolution, while IR systems used longer wavelengths to increase the ability to penetrate obscurants. The result is that both are converging on millimeter wavelengths.

The concept of vestigial components is another useful element of the natural evolution analogy. Just as humans have outgrown the need for

their appendix, fighters have outgrown the need for the gun. In air-to-air combat, an advanced off-boresight IR missile can function as a dogfighting missile in the unlikely event that USAF fighters are forced to engage in close combat. Despite this, the F-22 will incorporate a 20mm cannon, likely to be useless in modern air operations.

Another parallel with nature is the difficulties associated with identifying the evolutionary winners in the long term. The big, powerful radar SAMs of the Vietnam era are now vulnerable to USAF aircraft, while the smaller, highly mobile Strella's represent a significant threat. Changes in the environment make even short term predictions risky. For example, the Israeli Air Force had dominated the Mideast skies until all the air defense systems, which the IAF had always defeated separately, were integrated into a single system during the Yom Kippur War.

Finally, while the United States has no obvious peer competitor, competition in nature is the main force behind evolutionary developement. Israel's ability to turnaround from near defeat during the Yom Kippur War to complete domination of the air during engagements in the Bekka Valley is a classic example.

"Un-Natural" Evolution

Despite the value of the natural evolution analogy, this construct will fail under certain circumstances because there are many cases in which system development based on technological evolution does not follow the analogy of natural evolution.

First, unlike nature, system development does not depend on random change. Although this study stresses the chaotic nature of the development of IR systems, this should not be confused with the random mutations in nature that drive evolution. Unplanned or "other than planned" development successes still depend on individuals or organizations to solve a problem or recognize a solution that others had not seen or did not realize. This is chaotic, but not random. Since systems development does not occur over millions of years and involve billions of subjects, this is a crucial difference.

While system development is rational at some level, systems evolve in distinctly different ways. In nature, random change generates success that leads to evolution. It is a well-established military maxim

that defeat, not success, drives change, because those who lose seek to make changes that may be successful. The most notable historical example is the embrace of the WWI defensive mentality by the victorious French, while the defeated Germans developed the radically different blitzkrieg offensive. Similarly, Israel's near-loss in the Yom Kippur War led to new priorities and innovative tactics, while Syria's integrated air defenses remained relatively unchanged. On a smaller scale, the U.S. Navy's limited role in the Persian Gulf War spurred innovative solutions, such as radically changing the role of the F-14 Tomcat in order to quickly and cost-effectively prepare for future air operations. Since America is the biggest winner of the last decade and Russia is the most conspicuous loser, the un-natural aspect of losers evolving and winners stagnating raises profoundly important questions for the U.S. military.

Another important difference is that natural evolution tends to close out competition in nature as niches are filled, but for development based on technological evolution, the situation is exactly reversed. Sometimes the knowledge that a technology is possible gives the adversary an incentive, which explains in part why the USAF protected stealth technology for so long. In other cases, the new technological development is sold or given away and, as in the case of the Stinger missile, may end up in an unintended fashion in unfriendly hands. And, of course, espionage can sometimes allow a military competitor to catch up technologically, as see in the case of IR guided missiles when the Soviets developed their Atoll missile directly from stolen blueprints of the Sidewinder.[98]

While the U.S. military has maintained a significant lead in important technologies, civilian research and development efforts increasingly set the pace for technological development.[99] If commercial firms are the first to develop new technologies and are not encumbered by a slow procurement system, these organizations might be able to adapt to new technologies at a very rapid pace. For example, the development of IR systems may already be dominated by commercial organizations, particularly in the area of exploiting charged coupled devices (CCD) and uncooled thermal detectors. These two technologies will allow nearly any military force to field the types of IR systems that have been dominated by the U.S. military. In that case, special operations forces, whose tactical advantage has long rested on night vision devices, may no longer "own the night."

While the "un-natural" aspect of systems development is that it could occur by merger, chaotic system evolution by merger is a recurring theme. There are many examples. AMRAAM made radar guided missiles highly successful because it combined radar and inertial sensors. The Harrier and the Tomcat evolved into entirely different niches when merged with the all-aspect Sidewinder and LANTIRN, respectively. Egypt's integration of radar and IR SAMs and AA artillery in the Yom Kippur War was a successful merger on a massive scale. Brilliant munitions are an emerging success now that IR sensors can be merged with inertial sensors and cheap microprocessors. Potentially, IR missile developers may soon perform a similar evolution by merger.[100]

Another important difference is that nature stops at "good enough," but systems development based on technological evolution has no natural end. Bureaucracies focused on systems development create the pressure for continuous improvement for many reasons, including inertia which drives systems development past "good enough." This is probably the case where the USAF is developing an IR missile system in reaction to the Soviet Archer missile which cannot be justified based on the threat it poses to the USAF's dominance in the air-to-air roll.

The final difference in systems development evolution is that it can be the product of planning. Since it would be impractical to allow unplanned development to become the norm, logic and analysis are helpful for focusing the evolution of technological systems. Generally, the less obvious the solution, the more varied the experimentation and the more flexible and adaptable the organization must be. The evolution of the Israeli Python from the Sidewinder is an example of a practical and efficient solution to a straightforward problem.

Implications for the Revolution in Military Affairs (RMA)

A large portion of the U.S. defense establishment's modernization program focuses on implementing what is called the information-based RMA. The 2000 National Security Strategy notes that, "Exploiting the revolution in military affairs is fundamental if U.S. forces are to retain their dominance in an uncertain world." This is to be achieved by, "a carefully planned and focused modernization program."[101] While the concept of a "planned revolution" seems contradictory, the DoD

preference for planned development is likely to guide the RMA. Importantly, there are several lessons from the chaotic development of IR systems for tactical aviation that are applicable to this technological revolution.

First, since chaotic evolution works, a planned revolution is not necessary because the use of constant experimentation and improvement can result in revolutionary improvements in capabilities and systems. Second, chaotic evolutionary "revolutions" may be hard to recognize, as seen by the fact that the USAF still struggles with the implications of the new mode of medium altitude, beyond-visual-range air warfare that first appeared over the Bekka Valley almost 20 years ago. Since this mode of air warfare depends highly on command, control, communications, computers and intelligence (C4I), missiles, aircraft, and pilots, the information-based RMA may already have arrived for tactical aviation.

At the same time, chaotic evolutionary development happens in an unpredictable fashion. Since unplanned successes will undoubtedly affect the RMA, the Departmentof Defense must continue to experiment to preserve the most capable technologies and capabilities. The key is to manage chaotic development rather than avoid it.

One implication is that system developers should beware of vestigial components. For example, the U.S. Army's attempt to digitize the individual soldier has reached the point where considerable weight has been added to the soldier's existing load.[102] If the RMA will make U.S. military forces more capable, we must consider how to make those technologies practical in operational as well as developmental terms. A critical question for the RMA is the point at which the human in a combat platform is the equivalent of providing useful functions but involving disproportionate risk.

A critical lesson from the chaotic development of IR systems is that evolution by merger is consistently successful. Since an information-based RMA is highly dependent on advanced technologies in the fields of software and hardware development, the proponents of an information-based RMA should be aware of the dangers associated with in-breeding and tunnel vision. It is possible that if the RMA devolved into information experts who design complex information systems that are part of increasingly complex information networks that exist in isolation, it could miss the multi-disciplinary successes that produce revolutionary capabilities.

A further lesson from this analysis is that losers innovate and competition drives evolution. America already dominates the military application of information systems because we have no peer competitor and often engage in arms race with ourselves. Even our allies believe that we are evolving too quickly on the information front.[103] One lesson from nature is that competition is necessary for chaotic evolutionary development. While jointness has had positive effects on U.S. military capabilities, inter-service rivalry has proven useful. Many observers believe that a single Service could be a formula for stagnation in the development of new systems. This is an important consideration both as information operations migrate to the Space Command and there are pressures to create a separate joint space service.

Finally, an important lesson is that technological evolution is easier for successive generations of developers, especially for information systems given the rise of the internet and globalization. The corollary about the ascendancy of civilian technologies in leading edge IR systems is even more applicable to information systems. As the world's leading information-based society, it is not possible to turn back or slow down the pace of the information revolution in the society and the military. However, the U.S. dependence on information systems also makes the U.S. economy and military most vulnerable to new forms of warfare. One risk is that information warfare may be enabled by civilian developers and be employed on funding and time schedules that are inconsistent with DoD's development system.

VI. Conclusions

While orderly planned development is the preferred method for DoD and therefore receives most of the resources, deliberate planning also works. Under the DoD's highly structured planning and budgeting system, the U.S. military has been equipped with the finest military hardware in the world, including such highly successful examples as the radar systems in tactical aviation and the electronic countermeasures that defeat enemy radar systems. While both are products of the traditional system, this military materiel has been developed at great cost. Many acknowledge that the traditional development cycle is too lengthy to support the modern military.

As demonstrated by the infrared systems examined in this study, chaotic evolutionary development regularly occurs in DoD, has produced many combat successes, and may be cheaper and more responsive in a rapidly changing technological environment. The problem, however, is that this type of development is exploited on an ad hoc basis that competes with established plans, as seen in the development of the Sidewinder missile. The United States should shift more toward the chaotic evolutionary development model that is beginning to play a dominant role in the business world.

Unfortunately, under the current budget system, such a shift will be extremely difficult for DoD to accomplish. The next generation (Super Hornet, F-22 Raptor, and Joint Strike Fighter) are already planned and may exceed budget projections. Given this, there will be few resources to spend on innovative forms of development.

The key question is how to develop a culture and organization that takes advantage of chaotic evolutionary development. The most important step is for DoD to stop treating "chaotic" development as an aberration. This requires that unplanned or "other than planned" successes not be considered failures. At a time when the risks of failed experiments are low, evolutionary development should be embraced so that the forces of innovation, creativity, and "out-of-the-box" thinking are nurtured rather than tolerated. However, adding chaotic evolutionary development into the current budget system, which calls for long-range planning, will be difficult because it raises questions about DoD's system for planning, programming, and budgeting as it relates to experimentation and adaptation.

Fortunately, there is no lack of advice. Studies from the business world are full of advice on how to structure organizations in chaotic times. The original management guru, Tom Peters, suggests that organizations can "thrive on chaos."[104] Specific advice for the military is also available.[105] There are ways in which the Joint Forces Command can accelerate the pace of joint experimentation, and the establishment of a center for experimentation is an evolutionary step forward that needs to be vigorously pursued within the defense establishment.[106]

The U.S. Special Operations Command (USSOCOM) forces are a useful example. While our Special Operations Forces (SOF) are so small and specialized that it is difficult to draw broad conclusions about its activities, these forces have embraced infrared systems more fully than conventional aviators, and thus have taken advantage of chaotic evolutionary development. Importantly, evolution by merger is a constant theme in special operations, as seen in the merging of cargo aircraft, IR sensors, and Army artillery into special operations forces SOF fixed-wing gunships. The ability to react quickly to unfilled military niches is characteristic of SOF, which is consistent with the mission of using gunships to counter low technology transportation methods that were relatively immune to conventional USAF attack methods. While hardly a perfect model for development, procurement, or employment, SOF provide important lessons for how to incorporate chaotic evolutionary development more formally into the DoD acquisition process.

Finally, while this study has focused on the development of systems and technologies, a legitimate criticism is that it has focused on materiel rather than the organizational and doctrinal issues that constitute the other two legs of the triad for a true "revolution in military affairs." However, it is important to understand that the business community argues that the concept of chaotic evolutionary development can be applied to organization and methodology just as readily as it to systems development.[107] By implication, the overall concept of applying chaotic, evolutionary development is essential if the U.S. military is to continue to develop the technologies and capabilities that allow it to maintain technological superiority

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Notes

[1] Brown, Shona L. and Eisenhardt, Kathleen M., *Competing on the Edge: Strategy as Structured Chaos*, Harvard Business School Press, Cambridge, Massachusetts, 1998, p. 243. Brown and Eisenhardt apply evolutionary and chaos theory to business models. Competing "on the edge" means "the unpredictable, often uncontrolled, and even inefficient strategy that nonetheless defines best practice in the presence of pervasive change."
[2] Keegan, John, *The Second World War,* Viking Penguin, New York, New York, 1990 p. 92.
[3] Barker, Ralph, *The RAF at War*, Time-Life Books, Alexandria, Virginia, 1981, p. 142.
[4] Delve, Ken, *Nightfighter: The Battle for the Night Skies,* Sterling Publishing Company, Inc., New York, New York, 1995, pp. 157-181.
[5] Spector, Ronald H., *Eagle Against the Sun*, Vintage Books, New York, New York, 1985, p. 3.
[6] Delve, Ken, *Nightfighter: The Battle for the Night Skies,* Sterling Publishing Company, Inc., New York, New York, 1995, pp. 163.
[7] Keegan, John, *The Second World War,* Viking Penguin, New York, New York, 1990 p. 120.
[8] Miller, Edward S., *War Plan Orange*, Naval Institute Press, Annapolis, Maryland, 1991, p. 350.
[9] Hudson, Richard D., *Infrared System Engineering,* John Wiley & Sons, New York, New York, 1969, p. 9.
[10] Westrum, Ron, *Sidewinder: Creative Missile Development at China Lake*, Naval Institute Press, Annapolis, Maryland, 1999, p. 48.
[11] *Ibid*., p. 46.
[12] *Ibid*., p. 213.
[13] Gunston, Bill and Spick, Mike, *Modern Air Combat,* Crescent Books, New York, New York, 1983, p. 41.
[14] Westrum, Ron, *Sidewinder: Creative Missile Development at China Lake*, Naval Institute Press, Annapolis, Maryland, 1999, pp. 113, 119.
[15] *Ibid*., p. 136
[16] *Ibid*., p. 215.
[17] *Ibid*.
[18] *Ibid*., p. 209. See also, Gunston, Bill, and Spick, Mike, *Modern Air Combat,* Crescent Books, New York, New York, 1983, p. 188.

[19] "AMRAAM Meets Funding," *Aviation Week and Space Technology*, November 4, 1985, pp. 25-26.
[20] Gunston, Bill, *Guide to the World's Airborne Missiles,* Salamander Books, Ltd., London, United Kingdom, 1993, pp. 22-23.
[21] Westrum, Ron, *Sidewinder: Creative Missile Development at China Lake*, Naval Institute Press, Annapolis, Maryland, p. 218.
[22] The author, as a project engineer, "flew" about 150 hours in the simulator with the LANTIRN system.
[23] Clarke, Patrick E., "Litening Strikes," *Citizen Airman*, February 1999, pp. 12-13. Ironically, a LANTIRN-like pod called LITENING is a high priority for these same aircraft in the Air National Guard and Reserve.
[24] Cordesman, Anthony H., and Wagner, Abraham R., *The Lessons of Modern War, Volume III: The Afghan and Falklands Conflicts,* Westview Press, Boulder, Colorado, 1990, p. 4.
[25] *Ibid*., p. 174.
[26] *Ibid*.
[27] *Ibid*., pp. 176-177. The Stinger clearly had "a powerful tactical, if not strategic, impact on the Soviet decision to withdraw from Afghanistan."
[28] Ajami, Fouad, "Mr. Bin-Laden's Neighborhood," *U.S. News & World Report*, September 7, 1998, p. 26. Ajami notes that, "In Osama bin Laden, and in the phenomenon of the Taliban, the puritanical zealots who have conquered much of Afghanistan, some Arabs saw an American instrument being turned against its creator. It was in the last battle of the cold war, the drawn-out struggle for Afghanistan, that those radicals had been forged. They had been given American-made Stinger missiles and American money and succor. With such tools had bin Laden and his acolytes thwarted communism; now they have turned on the Great Satan. Most Muslims shed no tears for the United States. The Americans, after all, had sown the wind in the impenetrable hills of Pakistan and Afghanistan; now they are reaping the whirlwind."
[29] Gleick, James, *Chaos: Making a New Science*, Penguin Books, New York, New York, 1987, p. 8.
[30] Cordesman, Anthony H., and Wagner, Abraham R., *The Lessons of Modern War, Volume I: The Arab-Israeli Wars 1973 – 1989,* Westview Press, Boulder, Colorado, 1990, p. 80.
[31] *Ibid*., p. 82.
[32] *Ibid*. "Even though kill rates were low, the Arabs were pleased at the way their Soviet SAMs kept the IAF [sic: Israeli Air Force] at bay."

[33] *Ibid*. "The suppression effort took so long that much of the IAF's air superiority could not be brought to bear [sic: on the ground battles]."
[34] *Ibid*.
[35] *Ibid*., p. 85. The AAA and especially ZSU-34 represent deviations, which were highly effective in the low altitude environment, especially when pilots flattened out from the steep dives and split-S maneuvers that they used to avoid SAMs. The ZSU-34 was expected to be quite effective in any scenario in which tactical aircraft had to attack armor on the move, but this scenario never happened after the Yom Kippur War. Furthermore, planners ensured that ZSU-34 was one of the most heavily countered radar systems, partly because of their demonstrated effectiveness and because many were likely captured during the Israeli ground campaign.
[36] *Ibid*., p. 85.
[37] *Ibid*., p. 84.
[38] Westrum, Ron, *Sidewinder: Creative Missile Development at China Lake*, Naval Institute Press, Annapolis, Maryland, 1999, p. 197.
[39] Cordesman, Anthony H., and Wagner, Abraham R., *The Lessons of Modern War, Volume I: The Arab-Israeli Wars 1973 – 1989,* Westview Press, Boulder, Colorado, 1990, p. 85.
[40] *Ibid*.
[41] *Ibid*., p. 86.
[42] *Ibid*., p.201.
[43] *Ibid*., pp. 91, 201.
[44] *Ibid*., p.201.
[45] Gunston, Bill, *Guide to the World's Airborne Missiles,* Salamander Books, Ltd., London, United Kingdom, 1993, p. 42. The Israeli's had the same experience with the Maverick air-to-ground IR missile, but made exactly the opposite modification. The Maverick was also very accurate, consistently scoring direct hits on tanks. Since it is a massive missile that hits with high velocity on the vulnerable top armor, the kinetic energy of the impact is sufficient to kill a tank. The exploding warhead was superfluous, unless, as the Israeli's noted, shrapnel from the tank killed dismounted infantry who are in the vicinity. Therefore, the Israeli's removed the warhead from some of their Mavericks in order to generate significant weight savings, which increased the range and/or payload of the fighter and the range of the Maverick missile.
[46] Grant, Rebecca, *The Radar Game,* IRIS Independent Research, Arlington, Virginia: 1998, p. 27. While stealth aircraft are not invisible to

radar, the goal of stealth technology is to decrease the effective detection and tracking area of the radar.

[47] "USAF Generals Concur on B-1 Bomber Upgrade," *Aviation Week and Space Technology*, November 5, 1992, p. 70.

[48] Morrocco John D., "F-117A Fighter Used in Combat for First Time in Panama," *Aviation Week and Space Technology*, January 1, 1990, pp. 32-33.

[49] Morrocco John D., "New ASOCs Link Regional Airspace," *Aviation Week and Space Technology*, March 22, 1999, pp. 57-58, for a discussion of problems with integrating elements of ex-Warsaw Pact integrated air defense systems into NATO.

[50] Cordesman, Anthony H., and Wagner, Abraham R., *The Lessons of Modern War, Volume I: The Arab-Israeli Wars 1973 – 1989,* Westview Press, Boulder, Colorado, p. 186.

[51] *Ibid*., p. 193.

[52] *Ibid*., p. 187.

[53] *Ibid*., p. 186. "Unlike 1973, the IAF made SAM suppression one of its most critical objectives of the war. It was so successful in this area that it becomes difficult to discuss any aspect of performance by the Soviet SAM systems in Syrian and PLO hands."

[54] *Ibid*., p. 186.

[55] *Ibid*., p. 193.

[56] *Ibid*., p. 188.

[57] Cohen, Eliot A., *Gulf War Air Power Survey, Volume 5: A Statistical Compendium and Chronology*, U.S. Government Printing Office, Washington D.C., 1993, pp. 653-654.

[58] Keaney, Thomas A., and Cohen, Eliot A., *Gulf War Air Power Survey Summary Report,* Air University Press, Maxwell AFB, Alabama, 2000, p. 58.

[59] Murray, Williamson, *Air War in the Persian Gulf*, The Nautical & Aviation Publishing Company of America, Inc., Baltimore, Maryland, 1990, p. 180. Eventually 375 of 594 (63 percent) of the shelters were destroyed.

[60] Keaney, Thomas A., and Cohen, Eliot A., *Gulf War Air Power Survey Summary Report,* Air University Press, Maxwell AFB, Alabama, 2000, p. 18.

[61] *Ibid*., p. 201.

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62 Almond, Denise L., *Desert Score: U.S. Gulf War Weapons*, U.S. Naval Institute, Annapolis, Maryland 1991, p. 21.
63 Murray, Williamson, *Air War in the Persian Gulf*, The Nautical & Aviation Publishing Company of America, Inc., Baltimore, Maryland, 1990, p. 188.
64 Almond, Denise L., *Desert Score: U.S. Gulf War Weapons*, U.S. Naval Institute, Annapolis, Maryland 1991, p. 52.
65 *Ibid.*, p. 285. A significant use of IR technology during Operation Desert Storm was not for tactical aviation and thus did not receive much publicity. The "thermal sights" that were employed by U.S. armor forces seemed well suited to the ground battles during the Gulf War. While both sides' armor forces had large caliber, high velocity cannon that could engage targets at long ranges, the key to modern armored conflict is not the range of the gun, but the range of the sensors for detecting enemy armor. The sand and smoke on battlefields during the Persian Gulf War were transparent to the thermal sights of U.S. Abram tanks, Bradley fighting vehicles, and Apache helicopters. While U.S. forces could destroy Iraqi targets at long range, the Iraqi's were reduced to firing nearly blind at the occasional muzzle flash that penetrated the otherwise opaque atmosphere.
66 Scott, William B., "Bad Weather No Deterrent for New Long-Range Weapons," *Aviation Week and Space Technology*, May 3, 1999, pp. 66-67.
67 Author interview with Lieutenant Colonel Beth Kaspar, USAF, who served as a program manager at the Defense Advanced Research Projects Agency (DARPA).
68 Westrum, Ron, *Sidewinder: Creative Missile Development at China Lake*, Naval Institute Press, Annapolis, Maryland, 1999, pp. 27, 190.
69 Gunston, Bill, *Guide to the World's Airborne Missiles*, Salamander Books, Ltd., London, United Kingdom, 1993, p. 44.
70 Gordon, Michael R., and Trainor, Bernard E., *The General's War,* Little, Brown, and Company, Boston, Massachusetts, 1995, p. 218.
71 Scott, William B., "LANTIRN Gives Tomcat Night Attack Role," *Aviation Week and Space Technology*, June 10, 1996, pp. 40-43.
72 Keaney, Thomas A., and Cohen, Eliot A., *Gulf War Air Power Survey Summary Report,* Air University Press, Maxwell AFB, Alabama, 2000, p. 61. During the Persian Gulf War, radar SAMs accounted for 16 percent of the Allied losses, while low altitude defenses (IR missiles and AAA)

accounted for 71 percent. In the Kosovo conflict, radar missiles accounted for 100 percent of Allied losses.

[73] *Ibid*., p. 240.

[74] *Ibid*., p. 230.

[75] Even so, the single largest aircrew loss, an AC-130 aircraft, was due to an IR missile that was able to pick up the contrast of the large aircraft against the morning twilight sky, which was a time of day when the Gunship should not have been in the area.

[76] Morrocco, John D., "Kosovo Conflict Highlights Limits of Airpower and Capability Gaps," *Aviation Week and Space Technology*, May 17, 1999, pp. 31-33.

[77] Mann, Paul, "Kosovo Lessons Called Ambiguous," *Aviation Week and Space Technology*, June 28, 1999, pp. 32-36.

[78] Hallion, Richard P., *Control of the Air: The Enduring Requirement*, Air Force Museums and History Program, Washington, DC 1999, p. 65. For reference, F-15 and F-16 aircraft have shot down 130 enemy aircraft.

[79] Hughes, David, "Luftwaffe MiG Pilots Effective with Archer," *Aviation Week and Space Technology*, October 16, 1995, p. 39.

[80] Author interview with AFRL researcher on off-boresight missile and IRST and HMTS.

[81] Hughes, David, "Luftwaffe MiG Pilots Effective with Archer," *Aviation Week and Space Technology*, October 16, 1995, p. 39.

[82] *Ibid*.

[83] *Ibid*. This was the opinion of the USAF general in charge of procurement, while the MiG-29 was being evaluated. He also noted that the USAF already has a short range, off-boresight capability in the AMRAAM.

[84] Author interview with AFRL researcher on off-boresight missile and IRST and HMTS.

[85] Keaney, Thomas A. and Cohen, Eliot A., *Gulf War Air Power Survey Summary Report,* Air University Press, Maxwell AFB, Alabama, 2000, p. 245.

[86] The following data can be used to estimate the accuracy of munitions dropped from aircraft:

1972 -- 400 feet for conventional munition; 40 feet for precision munition, but very few U.S. aircraft have this capability;

1991-- 30 feet for precision munition, with 10 percent of the force having this capability;

1999 -- 10 feet for precision munitions, with 90 percent of the force having this capability;
1999 -- 40 feet for precision munitions with all weather capability, but few aircraft have this capability.

[87] Tirpak, John A., "Brilliant Weapons," *Air Force Magazine*, February 1998, pp. 48-53.

[88] Fulghum, David A., "Kosovo Conflict Spurred New Airborne Technology Use," *Aviation Week and Space Technology*, August 23, 1999, pp. 30-31.

[89] *Ibid*.

[90] *Ibid*.

[91] Coonts, Stephen, *Flight of the Intruder,* Naval Institute Press, Annapolis, Maryland, 1986, p. 3. Coonts noted that an A-6 pilot would penetrate enemy defenses by flying as low "as his skill and nerves allowed, which was very low indeed."

[92] Fulghum, David A., "Security Leaks and the Unknown Bedeviled Kosovo Commanders," *Aviation Week and Space Technology*, November 1, 1999, pp. 33-34.

[93] Wall, Robert, "SEAD Concerns Raised in Kosovo," *Aviation Week and Space Technology*, July 26, 1999, p. 75.

[94] *New World Vistas: Air and Space Power for the 21st Century: Attack Volume,* USAF Scientific Advisory Board, Washington, D.C., 1995, p.11.

[95] Fulghum, David A., "Improved Missiles Trigger Jammer Need," *Aviation Week and Space Technology*, September 27, 1999, p. 32.

[96] Gould, Stephen Jay, *The Panda's Thumb,* W.W. Norton & Co., New York, New York, 1980, p. 179.

[97] Gleick, James, *Chaos: Making a New Science*, Penguin Books, New York, New York, 1987, p. 8.

[98] Westrum, Ron, *Sidewinder: Creative Missile Development at China Lake*, Naval Institute Press, Annapolis, Maryland, 1999, p. 206.

[99] "Clinton Plans Major Initiative on Scientific Research," *Wall Street Journal*, December 31, 1999, p. A12, which notes that during the last 5 years, defense R&D declined slightly, while non-defense R&D increased by 12 percent.

[100] IR sensors have already incorporated many features that could make IR missiles even more threatening. Marginally more threatening dual-band seeker heads are already being offered as low-tech retrofit kits for older Strella's, but true multi-band seeker heads could be developed that would

be very difficult to spoof. The CCD imagery, which is the latest in cheap sensor technology, could easily be applied to missiles to reduce their vulnerability to countermeasures. Most threatening, the marriage of cheap multi-sensor seekers and cheap microprocessor power could produce truly revolutionary advances in the lethality of IR missiles.

[101] *National Security Strategy 2000*, U.S. Government Printing Office, Washington, D.C., 2000, p. 21.

[102] *Time Magazine*, January 1, 2000, p. 34.

[103] Morrocco, John D., "Kosovo Conflict Highlights Limits of Airpower and Capability Gaps," *Aviation Week and Space Technology*, May 17, 1999, pp. 31-33. A "retired senior French naval aviator" suggested the US should slow its drive for new digital battlefield enhancements to be more in line with its European allies in order to sustain cohesion of the transatlantic alliance.

[104] Peters, Thomas J., *Thriving on Chaos: Handbook for a Management Revolution*, Alfred A. Knopf, New York, New York, 1987, p. xii.

[105] Westrum, Ron, *Sidewinder: Creative Missile Development at China Lake*, Naval Institute Press, Annapolis, Maryland, 1999, p. 168.

[106] Johnstone, Mark A., Ferrando, Stephen A. and Critchlow, Robert W., "Joint Experimentation: a Necessity for Future War," *Joint Forces Quarterly*, Autumn/Winter 1998-99, pp. 15-24.

[107] Brown, Shona L., and Eisenhardt, Kathleen M., *Competing on the Edge: Strategy as Structured Chaos*, Harvard Business School Press, Cambridge, Massachusetts, 1998, p. 243.

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